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Reducing Driftable Fines in Aerial Application of Pesticides -

A Reverse Venturi Atomization Chamber

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Abstract. *Spray drift is one of the most significant issues presently facing agricultural applicators throughout the United States. In American agriculture, up to half of the crop production materials applied are delivered to the crop by air. This method of application is highly valued by the farmer and contributes to American agricultural productivity. However, material that drifts off-site is of concern. Material not applied to the target crop or pest is a financial loss for the farmer and a potential liability for the applicator if damage occurs. Off-site drift also represents an environmental liability, particularly as habitat and water quality concerns demand more and larger buffer and/or no-spray zones.*

The reverse venturi atomization (RVA) chamber is a potential strategy to mitigate the problem of off-site drift. Current practice delivers liquid material through a nozzle, under pressure, and utilizes air shear for at least a portion of the atomization. This atomization creates a range of droplets with those in the < 200 micron range, known as fines, particularly susceptible to off-site drift. As airspeed increases, so does the effect of air shear on the atomized droplets, resulting in smaller droplets shattering or fracturing into more fines. By creating spray droplets within the RVA chamber, we propose to minimize the effect of air shear, reduce the overall percentage of droplets in the < 200 micron range, and ultimately reduce the potential for off-site movement of material applied by air.

Keywords. reverse venturi, spray drift, atomization

Introduction

Spray drift is one of the most significant issues presently facing agricultural applicators throughout the United States. Agricultural applicators are committed to the management of chemical drift and take responsibility on a daily basis for making good decisions in the field. Material that drifts off-site is material that is not applied to the target crop or pest and represents both wasted time and wasted material. This equals increased costs for both the farmer and applicator and subsequently to the public and consumer. Materials such as herbicides and defoliants that drift off-site can be a serious financial liability, particularly if surrounding crops are negatively impacted either by actual crop damage or by unacceptable, off-label, residues present on the crop.

Environmental concerns for air and water quality protection and for habitat and endangered species protection make off-site spray drift an increasingly "hot issue". Many waterways, protected habitats and endangered species are adjacent to agricultural areas where materials are applied. Drift into/onto protected or particularly sensitive areas presents a serious financial liability for the applicator, as well as an environmental liability.

Off-site spray drift is also an urban encroachment concern. As suburban populations increase and spread, encroaching on formerly rural and agricultural areas, buffer zones and/or no spray zones between populated areas and agricultural areas will increase in number and in total acreage. More of these buffer and no spray zones increases the likelihood of conflict between aerial applicators and the public. It simply will become more and more difficult to avoid them. The more complaints that are registered and the more law suits filed, the more likely that additional regulations and/or restrictions will be enacted.

In summary, the minimization of off-site drift is to the benefit of all concerned - aerial applicators, farmers, regulators, the public and the environment.

Background and Rationale

The majority of agricultural materials are applied as a liquid solution from a nozzle-atomizer by either aircraft (fixed-wing or helicopter) or ground-based methods. In either scenario, the nozzle-atomizer unit must perform two functions. First, it must discharge the solution at a controlled and metered rate to provide appropriate coverage and accurate dosage for the material being applied and the crop/pest being treated/targeted. Second, the nozzle-atomizer must break the solution into appropriately sized small drops for dispersal onto the target. Most nozzle-atomizers in use on agricultural sprayers produce a range of drop sizes approximating a Gaussian or bell curve distribution range, which may be somewhat skewed towards smaller drops. It has not been determined that the production of a single-size drop would produce the most desirable coverage of plant surfaces, but it is widely understood that a narrowed spectrum, which eliminates both the smallest and largest drops in the range, would be a desirable improvement in nozzle-atomizer design. By concentrating the drop size in a narrower range, the smallest, most drift-prone drops (fines) and the largest drops that produce poor coverage would be reduced significantly.

Most nozzles utilize traditional designs, either hydraulic pressure, fan, cone, solid core dispersion, or rotary screen types (Akesson and Yates, 1989). These nozzles, when used on an aircraft, release the spray solution into the airstream and utilize both the nozzle and air shear for atomization.

Although aerial applications have been in practice for many years, in most situations, aerial applicators have used “off-the-shelf” nozzles, originally designed for ground applications, not aircraft. Newer, more advanced nozzles are more convenient in actual use. Angle of deflection and orifice size can be changed quickly and easily. Applicators have been creative in combining nozzles and spray pressures, and diligent in their attention to environmental conditions, to obtain satisfactory application patterns for the many materials now applied by air. There has been minimal attention, however, to the matter of fines. What is needed is a system that is relatively easy to use that addresses fines and hence drift. Unfortunately, as air speed increases, so does the percentage of driftable fine droplets <200 μ. Air shear “shatters” the large droplets into “fines” and as air speed increases, so generally does turbulence, increasing the percentage of fines.

Single-size droplets have been produced with or without an airstream under controlled laboratory conditions (Yates et al., 1983a and 1983b, Womac et al., 1992). Unfortunately, no commercially suitable atomizers producing single-sized droplets are presently on the market, especially for aerial applications. Work with magneto-strictive and piezo-electric pulsed jet nozzles (Wilce, et al., 1974), and microjet airfoil systems (Yates et al., 1983a) appeared promising. Unfortunately, both systems were limited by the very small orifices required to produce a useful drop size, ~ 300 μ. The small orifices were easily blocked and clogging problems doomed them as not commercially feasible. Subsequent work utilized the wire brush theory, hoping to produce useful drop size by leading drops down a wire brush placed in an airstream to obtain a narrowed drop size range (Akesson and Gibbs, 1990), but this has yet to provide a solution that is viable on a commercial scale.

The goal of this research proposal is to develop a method of dispensing agricultural materials, in a dependable manner (ultimately from a fixed-wing aircraft), that will produce an appropriate size range of droplets, with a reduced percentage of fines < 200 μ (driftable fines). Achieving this goal will greatly reduce the potential for off-site spray drift.

Work by Akesson and Yates, 1974, has determined the critical air velocity (the speed at which droplets break up) and corresponding drop sizes at which this occurs. This work explored a variety of nozzles and atomizers, using water, in the wind tunnel at the University of California, Davis. The results of these investigations follow and mph values have been included as convenient points of reference for this proposal. As can be seen in Table 1, at common aircraft speeds of over 100 mph, drops larger than ~380 μ can be broken up into smaller droplets and, subsequently there is an increased percentage (or strong likelihood) of driftable fines.

TABLE 1 Critical air velocity at which droplets break up

Critical Velocity, (km/h / mph)	**Drop Size (microns, μ)**
80.5 / ~ 50 mph	1500
105 / ~ 65 mph	900
137 / ~ 85 mph	535
161 / ~ 100 mph	385
241 / ~ 210 mph	170

For our purposes, another important data set (Akesson, 1994) describes the comparisons of “relative span” (R.S.), a measure of the drop size range, expressed as:

$$R.S. = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}}$$

The lower the R.S. value, the “tighter” the drop size range and the more uniform the drops produced. When R.S. values are $\leq$ 1, the range of drop size is equal to or narrower than a normal or Gaussian distribution. As R.S. values increase, the drop size range becomes wider.

<u>Micro orifices</u> of 125 μ produced a very narrow drop spectrum in an airstream of 97 km/h, particularly when pulsation was employed. When the same orifice was placed in an airstream of 166 km/h, the pulsation did not appreciably improve the results. Also, micro orifices experienced problems with clogging and using larger orifices did not yield similar results because the larger spray stream was more susceptible to break up in the airstream. Other investigators theorized that if liquid drops were emitted at air stream velocity, they would not be further broken up, although this only considered the relative velocity factor and did not account for other factors. The most notable factor of concern is the increased liquid pressure in the system required to increase the emission velocity of the fluid. Pressures $\geq$ 100 psi act to break up the stream at emission by inducing turbulence within the stream.

Other nozzles also were considered. RD series <u>hollow cone atomizers</u> generated larger drops than standard disc-core nozzles, but the drop size range was unacceptable. <u>Pre-orifice fan type nozzles</u> allow control of pressure and flow, resulting in lower pressure at the discharge fan and generally larger drops. The spectrum range, however was not improved with these designs when compared to standard fan nozzles. <u>Deflector fan atomizers</u> were also evaluated. Bouse (1992), reported a reduction of small drops and reduced drift with these units, but the tests at UC Davis were inconclusive and did not confirm a significant reduction in the drop size range. <u>Hollow cone nozzles</u> were designed to produce large drop size sprays and utilize a tangential entry, whirl chamber design. Although drop sizes were somewhat smaller, the range remained similar to deflector fans and increased air speed again broke up the drops resulting in no overall improvement. Finally, <u>brush atomizers</u> were evaluated in an attempt to exploit the brush potential for reduced drop size range as well as increased drop size. Several wire brush designs were attempted but experienced sheeting, large fragments and turbulence behind the brush. A nylon brush design gave somewhat better results, but produced a turbulent wake due to its thickness, and denied the investigators the more uniform size drops they had anticipated.

Example 1 Comparison of two flat fan nozzles (8010, 8020) under the same conditions at 50 (reference), 100 and 150 mph airspeeds, performed in the UC Davis wind tunnel. Both nozzles were oriented at 0^o to the air stream and operated at 40 psi using water. The key criteria predicting off-site drift is the percentage of droplets in the < 200 μ range. As air speed increased from the reference point of 50 mph, the number of droplets (% volume of particles) less than 200 μ increased 2.9-3.0% at 100 mph and 18.8-18.4% at 150 mph.

Example 2 Comparison of volume mean diameter produced by a CP drift reduction high volume flat fan nozzle under the same conditions at two air speeds. The nozzle utilized the same orifice (15), was operated at 40 psi and oriented at 0^o to the airstream. The key criteria for our evaluation was the percentage of droplets < 200 μ. At 50 mph, the percentage was 2.15% and at 100 mph, the percentage increased to 9.67%. This is a four-fold increase in driftable fines. The effect of increased airspeed, which increases air shear and results in the formation of more fines, clearly increases the potential for off-site movement or spray drift (Kirk, 2000 and Kirk, 2001).

Droplets formed at slower air speeds (and emanating from a nozzle at 0^{o} to the airstream) experience less wind shear and, subsequently, producing less driftable fines. When combined with appropriate orifices and fluid pressures, these slower air speeds are a primary reason why material applied by helicopter has less potential for drift. Depending on the nozzle and application scenario, sometimes a combination of higher fluid pressure and a smaller orifice will accelerate the fluid closer to actual air speed, reducing the wind shear effect on the droplets, and provide the desired size droplet. How can we utilize this information and apply this concept to high-speed, fixed-wing aircraft applications?

Based on the information discussed above and the principal investigator's expertise in the aerial application of a variety of materials, the rationale for this research was that an atomization chamber can be utilized to minimize the wind shear effect on the spray droplets, reducing driftable fines.

To address the problem of off-site drift by agricultural materials, a prototype Reverse Venturi Atomization (RVA) chamber has been constructed (Figure 1). The chamber has three sections: 1) a constricted opening known as a diffuser, that is widely rectangular and opens into, 2) a larger chamber, known as a settling chamber, that houses a spray nozzle directed aft towards, 3) a constricted exit, the annulus. This unit was mounted in the wind tunnel for testing purposes, simulating the conditions that would be found when the unit was attached to a fixed-wing aircraft.

As air enters the RVA chamber, it decelerates to approximately one half the outside airspeed as it reaches the center of the RVA chamber, due to the proportions of the chamber. At the center of the chamber, droplets are formed with a nozzle at 0 degrees deflection from the airstream, minimizing air shear. The droplets then continue through the chamber, which constricts toward the exit, accelerating the droplets to or close to the original, external speed. The droplets then enter the airstream as they were formed and without the fracture or shattering due to abrupt changes in air speed. The prototype RVA chamber (Figure 1) is currently over-sized and primarily a test vehicle to demonstrate the reverse venturi chamber concept as a viable technique to reduce driftable fines.

Air flow $\rightarrow$

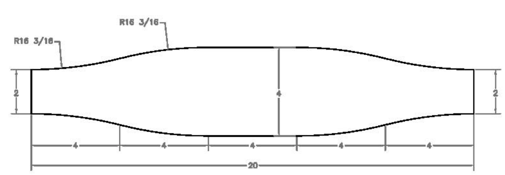


Figure 1. The prototype RVA chamber

Results

The primary objective of the USDA SBIR Phase I proposal was to develop a unit that will produce a droplet spectrum with a reduced percentage of fines (droplets of < 200 µ) when mounted on and operated from a fixed-wing agricultural aircraft. A prototype Reverse Venturi Atomization (RVA) chamber had been developed and has since been modified (see below). The RVA chamber design was based on the hypothesis that if atomization of spray material (droplet formation) is accomplished in a low air velocity environment (i.e., within the chamber and in a velocity range similar to that of a helicopter), then the droplets formed in this controlled environment could then be accelerated to actual aircraft air speed (100-120 mph) while maintaining the same droplet spectrum (i.e., with minimal droplet shatter/fracture and a reduced percentage of fines < 200 μ).

To test this hypothesis, the following technical objectives were addressed in the Phase I project:

1. Investigate air flow behavior in the prototype RVA chamber
2. Determine optimum RVA chamber configuration(s)
3. Investigate changes in droplet behavior in several configurations of the RVA chamber.
4. Evaluate five (5) nozzles in three wind speeds (50, 100 and 150 mph)

Objectives 1, 2 and 3 - Air flow behavior, chamber configuration, droplet behavior

Three versions of the prototype RVA chamber have been constructed of plexiglas, all 20 inches long, 7 inches wide and 2-4 inches high at the in-flow and out-flow points. Each has three sections: 1) a diffuser that opens into, 2) a settling chamber, housing a spray nozzle directed aft towards, 3) a constricted exit, an annulus. Due to the specific proportions of the chamber, as air enters the RVA chamber diffuser, it decelerates to approximately one half the outside airspeed as it reaches the settling chamber. Droplets are formed at the center of the chamber with a nozzle at 0 degrees deflection from the airstream, minimizing air shear to the droplets. The droplets then continue through the chamber, which narrows, accelerating the droplets up to or near the original, external airspeed as they reach the annulus and travel out into the actual airstream. Thus, the droplets enter the outside airstream in approximately the same range of sizes as when they were formed and without the shattering observed with abrupt changes in air speed. Modifications to the shape and configuration of the chamber can be made so that the chamber will function on either fast or slow aircraft, yet the airspeed within the chamber (that is determined to be optimum for a particular nozzle) will remain constant.

Chamber 1: The chamber described in the original proposal (see Figure 1, above).

Chamber 2: This chamber has the same entrance opening as Chamber 1, but the settling chamber is broken at the center point and the top and bottom surfaces are 1 inch higher and lower, respectively, totaling 6 inches high; the exit is 4 inches high.

Chamber 3: This design was recommended by consultant aerodynamic engineer, Will Peschel, and <u>reverses</u> the design of Chamber 2. This orientation, known as a boundary layer ejection slot, effectively draws the boundary layer along the top and bottom surfaces of the chamber out of the chamber and virtually removes the boundary layer effects (drag or friction of the air against the upper and lower chamber surfaces) seen in the previous two designs.

Air flow $\rightarrow$

Figure 2. Chambers 2 (left), and 3 (right).

In order to evaluate the airflow through and performance of the spray droplets within the chambers when operated in the wind tunnel, W. Peschel, consulting aerodynamic engineer, constructed a Pressure Survey Rake (PSR). This instrument has 18 pressure tubes and two static pressure orifices. These (20) are connected to a manometer board with 23 total tubes. Of the three remaining tubes, two measure static pressure from the wind tunnel aft the RVA chamber and the wind tunnel's pitot tube, and the third tube measures the pitot tube pressure side. The PSR was particularly helpful in evaluating the boundary layer effects in the three chambers (see Table 2).

Tests of the three prototype chambers were conducted in the wind tunnel at UC Davis at 100 and 150 mph airspeed. All three chambers were mounted in the same location and orientation in the wind tunnel. The PSR was mounted on a fixed track in the wind tunnel, allowing the investigator to position the PSR precisely within each chamber. T_1, T_2, T_3, and T_4 are equally spaced pressure tubes, top to bottom, on the PSR. The first measurement was taken with the PSR tip at the chamber's exit point. This was point 0. Four additional measurements were taken at 2, 4, 6 and 8 inches as the PSR was drawn into the body of the chamber by two inch increments.

As can be seen in Table 2 below, Chamber 1 demonstrates a significant boundary layer. The speed of the air closest to the upper and lower surfaces (T_1 and T_4) is consistently slower than the air in midstream (T_2 and T_3). The airspeed at the midpoint of the chamber (point 8) is much reduced from the 100 mph entrance speed, which was a desired outcome. Chamber 2 shows more consistency between the readings at each point, but there is still a noticeable boundary effect. The higher speed throughout the chamber and particularly at the midpoint (point 8) may not prove acceptable. Airspeed readings in Chamber 3 are remarkably consistent at each point, demonstrating virtually no boundary layer effect along the top or bottom of the chamber. Boundary layer effect(s) on the sides of the chambers have yet to be determined. In addition, the airspeed at the midpoint of the chamber (point 8) is the slowest of the three chambers, which should assist us in attaining our goal of reducing fines.

Based on the results presented in Table 2, Chamber 3, the "Enhanced RVA Chamber", appears to be the most promising configuration. The upper and lower boundary layers have been virtually eliminated and the airspeed within the chamber (8" point) is the slowest.

Chamber performance was also evaluated compared to external, free stream air velocity. The goal was to reduce the speed of the air within the chamber (8" upstream, where the nozzle would be located) as much as possible and to subsequently accelerate the air so that at the exit point it is as close to the free stream air velocity as possible. The general design parameters of the chamber are such that the airspeed within the chamber will be approximately half the external speed. Table 3 summarizes the performance of the three chambers in comparison to the free stream velocity. Theoretically, the airspeed ratio should be 0.5. Chamber 3 gave the greatest proportional reduction in air velocity within the chamber, 0.466, and the highest proportional increase in velocity at exit from the chamber, 0.934, resulting in an airspeed ratio (U/E) of 0.499, the closest to 0.5. Chamber 1 did less well with an airspeed ratio of 0.589 and Chamber 2 did very poorly. On the recommendation of W. Peschel, Chamber 2 was abandoned entirely and further testing was performed with Chamber 3.

TABLE 2. Pressure Survey Rake (PSR) results

PSR readings, in mph, from the four tubes (T_1 - T_4, in horizontal orientation) at five points, in two inch increments, from the chamber exit (0") into the mid-section (8" from the exit) of the RVA chamber while mounted in the wind tunnel; wind at ≈100 mph and 150 mph.

	100 mph					150 mph				
Chamber 1	**0"**	**2"**	**4"**	**6"**	**8"**	**0"**	**2"**	**4"**	**6"**	**8"**
T_1	89.6	87.9	75.5	58.8	55.2	133.8	121.8	102.8	90.7	87.3
T_2	94.0	92.4	79.4	63.8	58.8	143.3	131.5	109.5	93.5	88.5
T_3	96.7	93.5	80.7	68.4	58.8	140.4	129.1	104.8	89.6	86.7
T_4	91.3	87.9	80.0	69.1	57.0	131.8	118.9	93.0	78.8	79.4
average T_1- T_4	92.9	90.4	78.9	65.0	57.5	137.3	125.3	102.5	88.2	85.5
	100 mph					**150 mph**				
Chamber 2	**0"**	**2"**	**4"**	**6"**	**8"**	**0"**	**2"**	**4"**	**6"**	**8"**
T_1	93.5	91.3	80.0	74.1	67.6	146.5	138.2	123.5	113.2	110.5
T_2	95.7	93.5	82.5	75.5	70.6	147.2	138.2	122.7	111.8	109.1
T_3	97.2	95.1	85.0	76.1	73.4	141.5	133.8	116.7	105.8	103.8
T_4	95.1	92.4	85.0	75.5	71.2	134.5	127.5	106.7	96.2	93.5
average T_1- T_4	95.4	93.1	83.1	75.3	73.0	142.4	134.4	117.4	106.8	104.2
	100 mph					**150 mph**				
Chamber 3	**0"**	**2"**	**4"**	**6"**	**8"**	**0"**	**2"**	**4"**	**6"**	**8"**
T_1	95.7	88.5	73.4	58.8	51.4	143	130	100	86	76
T_2	95.7	88.5	73.4	58.8	51.4	143	130	100	86	76
T_3	95.7	88.5	73.4	58.8	51.4	143	130	100	86	76
T_4	95.7	88.5	73.4	58.8	51.4	143	130	100	86	76
average T_1- T_4	95.7	88.5	73.4	58.8	51.4	143	130	100	86	76

TABLE 3. Comparison of chamber performance to free stream air velocity

Ratios of average air velocity within the chamber versus wind tunnel air velocity (100 and 150 mph) at 8" upstream and at chamber exit.

Chamber #	Wind tunnel air speed (T), average, mph	8" upstream air speed (U), average, mph	Ratio to tunnel air speed (U/T)	Velocity at exit (E) average, mph	Ratio to tunnel air speed (E/T)	Air speed ratio (U/E)
100 mph						
Chamber 1	101.3	52.5	0.52	89.1	0.88	0.59
Chamber 2	101.6	70.8	0.70	92.1	0.91	0.77
Chamber 3	99.8	45.6	0.47	91.3	0.93	0.50
150 mph						
Chamber 1	151.0	85.5	0.57	137.3	0.91	0.62
Chamber 2	150.0	104.2	0.69	142.4	0.95	0.73
Chamber 3	149.0	76.0	0.51	143.0	0.96	0.53

To evaluate the airflow through the chambers (with airspeed at 100 mph), PSR readings were taken within the chamber along the center line as well as laterally both at the entrance point and 8" into the chamber. Again, Chamber 3 provided the best results. Along the axial (center line) at all four measurement points on the PSR, airspeed decreased from 95.65 (chamber exit), to 73.40 (4 inches), to 58.79 (6 inches) and finally to 51.41 mph (8 inches upstream), demonstrating both the desired reduction in airspeed within the chamber and acceleration to very close to wind tunnel airspeed at the chamber exit point.

Table 4, below, provides a comparison of PSR readings in Chamber 3 taken at the exit point and 8" upstream when the PSR was shifted laterally. Although there was some variation at the exit point (0 inches), once within the chamber (8 inches upstream), the readings were again very consistent. Some boundary layer effects were seen along the sides of the chamber as the PSR was moved laterally (8 inches upstream). These effects may have been exacerbated by minor irregularities in the shape of the chamber. An aerodynamically smoother chamber is likely to improve nozzle performance and minimize droplet fracture or shatter within the chamber. Chamber 3, the "Enhanced RVA Chamber", also proved to be the most suitable for this application.

TABLE 4. Lateral airstream performance in Chamber 3

Comparison of wind speeds at the exit (0 inches) and 8 inches upstream from Chamber 3, calculated from PSR readings at both 2 and 3 inches from the right and left of each side of the chamber wall. Data are the average of three tests. ΔP = Difference between pressure readings at S_0 and T_X; S_0 = static wind speed; T_X = individual pressure tubes on the PSR; wind tunnel speed = 100 mph.

PRESSURE SURVEY RAKE LATERAL LOCATION								
	Exit (0 inches)				8 inches upstream			
	2" left	3" left	2" right	3" right	2" left	3" left	2" right	3" right
ΔP	mph	mph	mph	mph	mph	mph	mph	mph
S_0-T_0	98.27	98.27	96.71	97.75	97.75	97.23	96.18	96.18
S_1-T_1	84.36	92.41	94.04	95.12	37.33	47.29	50.41	42.78
S_1-T_2	83.14	91.86	94.04	91.86	37.33	47.29	50.41	42.78
S_1-T_3	84.36	92.41	94.04	91.86	37.33	47.29	50.41	42.78
S_1-T_4	87.32	94.04	94.04	95.65	37.33	47.29	50.41	42.78

Based on these data and in consultation with W. Peschel, Chamber 3 was determined to be the most appropriate design for the RVA and was used for the subsequent nozzle evaluations. Further refinements and modifications, however, are anticipated and will be accomplished under a future SBIR Phase II proposal.

Objective 4 - Nozzle evaluation

The proposal indicated five nozzles would be evaluated and, in fact, eight have been tested to date. The primary criteria for the nozzles was that the spray pattern from the nozzle would not strike the chamber walls (top, bottom or sides).

Protocol:

1. Bench test nozzles, outside the chamber, at various spray pressures to assess spray patterns.

2. Bench test nozzles, inside the chamber, under static conditions (without airflow) to assess spray patterns within the chamber.

3. Test nozzles in the wind tunnel at 50, 100 and 150 mph wind speed to assess spray patterns and atomization profiles.

4. Test nozzles in the wind tunnel in the RVA chamber at 100 and 150 mph wind speed to assess spray patterns.

5. Test nozzles in the wind tunnel at five locations within the chamber at 100 and 150 mph to determine optimum location for spray nozzle.

By industry convention, many flat fan and even fan nozzles are numbered or coded based on their degree of fan and gallons per minute rating at 40 psi. For example, a 2505 nozzle is a 25 degree fan that applies 0.5 gallons per minute at 40 psi and a 4010 is a 40 degree fan that applies 1 gallon per minute at 40 psi. Other types of nozzles have similar coding conventions.

Nozzles tested:

H1/8VV-2505, Spraying Systems Co., Wheaton IL.

A 25 degree flat fan nozzle, this unit worked well, demonstrating a very flat pattern, at the lower pressure of 20 psi, but at 50 psi the spray began to contact the side wall of the chamber. Therefore, data were collected only for the 20 psi setting at 100 mph.

1/8MEG-1503, Spraying Systems Co., Wheaton, IL

An even fan nozzle, this unit has a desirable, narrow lateral spray pattern, but the unit's deep vertical pattern impacted the top and bottom of the chamber at spray pressures greater than 20 psi. However, at 20 psi and 100 mph, the spray did not contact the chamber walls and this nozzle demonstrated a 71% reduction in driftable fines. At 150 mph, the nozzle performed well at both 20 and 50 psi, without any spray contact with the walls of the chamber. Therefore, this nozzle may be appropriate in certain circumstances or for different chamber configurations.

D-5, Spraying Systems Co., Wheaton, IL.

A disc orifice, solid stream nozzle, the spray pattern (jet) brake up takes place past the exit of the chamber. This unit did not perform as well overall as other nozzles, working well at 100 mph, but less satisfactorily at 150 mph. .

Microfoil .013, Bishop Equipment Mfg., Hatfield, PA.

The standard Microfoil nozzle is symmetrical, having micro tubes (jets) in a single row along the aft edge. The cord is two inches long and 0.75 inches thick; overall, the unit is six inches long with 60 micro tubes, each with an inside diameter of 0.013 inches, exiting the aft end. The spray exits this nozzle in a sheet. Because the boundary layers on the walls of the chamber have not been removed (only the top and bottom), this nozzle had to be modified to work in the RVA chamber. Fourteen tubes on each end were plugged and the leading edge of the nozzle was extended 0.5 inch, giving it a sharper leading edge. Both outside and inside the chamber, the sheet of spray on the right side of the nozzle was pushed up or lifted from the horizontal and the spray on the left side was pushed down or depressed from the horizontal. This effect was aggravated with increased airspeed, but illustrates the sensitivity of this type of nozzle to minor misalignments or to chamber irregularities. The nozzle worked at every station except the 12 inches, where the spray began to contact the top and bottom of the chamber. It should be noted that this nozzle operates best at only 5 psi and, thus, this was the rate used for this nozzle, rather than the 20 or 50 psi used with the other nozzles.

H1/8VV-0003, Spraying Systems Co., Wheaton, IL.

A solid stream nozzle, this unit has an extremely tight core spray pattern that holds together for 18-24 inches at low pressures and longer distances under higher pressure.

H1/8VV-1505, Spraying Systems Co., Wheaton, IL.

A 15 degree flat fan nozzle, this unit performed the best of all nozzles tested in the chamber and worked well at both 20 psi and 50 psi. It has a very flat and narrow spray pattern and, if selected, the exit of the RVA chamber could be half the current size with no impact of the spray on the walls.

Monarch, H-535 #.60-15, Monarch Nozzle Co., Pleasantville, NJ.

A 15 degree flat fan nozzle, this unit also has a good spray angle (narrow laterally), but the spray pattern is deep (vertically) and at higher pressures impacted the top and bottom of the chamber at 100 mph. This was not observed at 150 mph. It was also discovered that there were several burs in the cut slot which distorted the spray pattern. This was an important observation. It will be critical for the nozzles in use to be inspected for manufacturing defects of this type and others to insure proper operation of the RVA chamber(s).

TubeJet .0625, a custom-made nozzle, .0625" ID, 2" long tube.

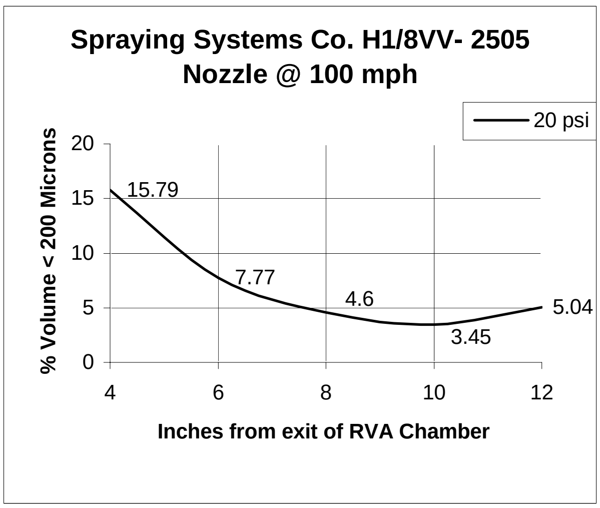
This is a simple tube orifice, solid stream nozzle. Although it operates well at 50 psi and is not prone to clogging, it only demonstrates a 21% reduction in driftable fines at 100 mph and other nozzles were more successful.

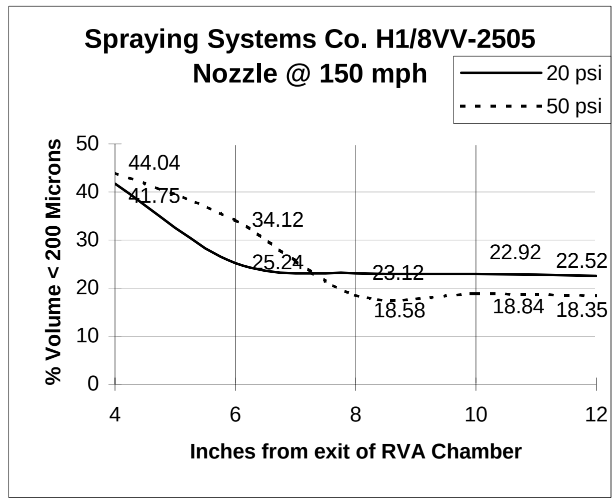
The spray from some nozzles struck the chamber walls under static conditions, but did not with air flow. The air flow over flat and even fan nozzles had a tendency to flatten the spray pattern while narrowing the angle of the spray pattern. This allowed the spray to pass through the chamber without contacting the chamber walls. Similar tendencies were seen with other nozzle types.

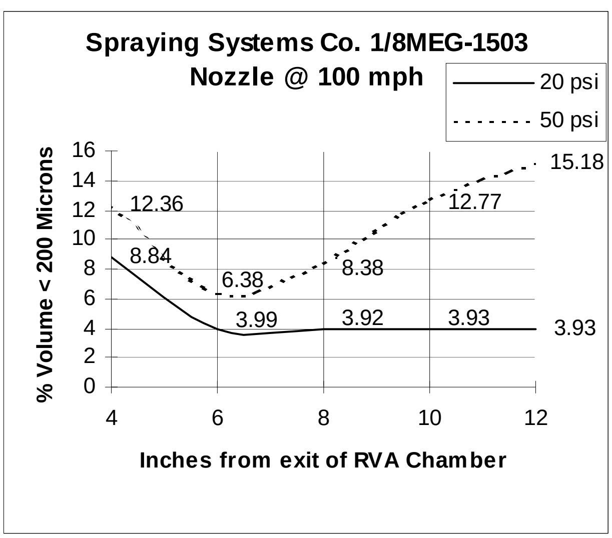
Considering the differences in the various nozzles and their spray patterns, as well as their performance at different pressures, we next investigated the impact that nozzle placement within the chamber would have on the percent of droplets $< 200\ \mu$. Depending upon the characteristics of a particular nozzle at a given pressure, it was possible that "mid-chamber" was not the optimal location for the nozzle. A sliding tube was constructed that would position the nozzle along the center axis of the chamber. Two inch increments were selected for nozzle evaluation purposes. Figure 3, below, shows the percent of spray volume $< 200\ \mu$ at 2 inch increments in the RVA chamber at 20 and/or 50 psi for seven of the eight nozzles tested. The Microfoil nozzle was tested at 5 psi. Note that the scale of the y-axis differs between nozzles due to the range of values obtained. All nozzles were tested in the same manner at about the same time to minimize variation but our goal, although quantitative, was primarily comparative in nature.

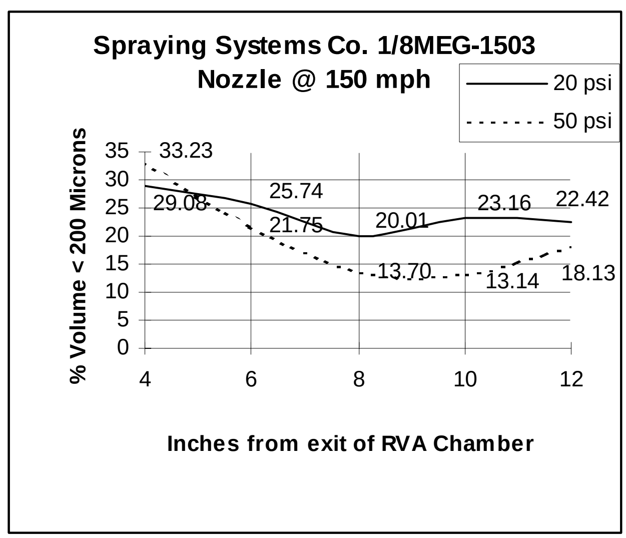
Eight nozzles were tested at both 100 and 150 mph and each demonstrated different but often similar curve characteristics (see Figure 3, below), indicating different optimum placement of the nozzle within the chamber (distance from the annulus) at a particular airspeed and fluid pressure. At both airspeeds, most nozzles performed better, demonstrating a lower percentage of fines, at 50 psi than at 20 psi.

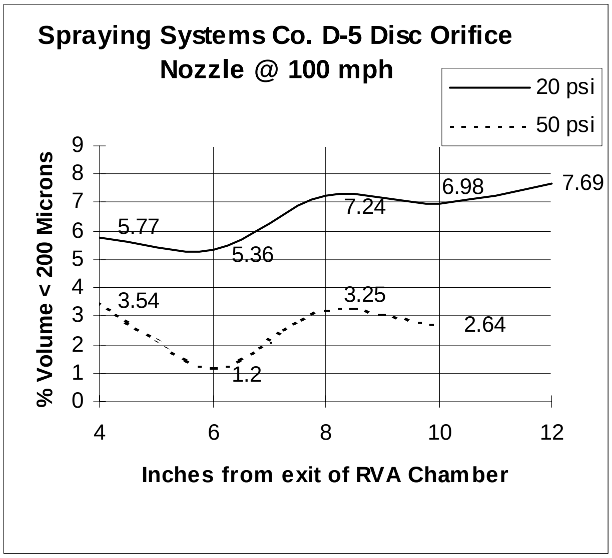
Figure 3
Graphical representation of % volume < 200 μ (fines) produced by all eight nozzles tested, using water, in the RVA chamber at 100 and 150 mph. One nozzle was run at 5 psi and the others at both 20 and 50 psi (with one exception, see below). Nozzles were tested from 4 to 12 inches from the exit of the chamber, in 2 inch increments, along the center axis of the chamber. Note that to display the curves well, the y-axes are not consistent between the various nozzles.

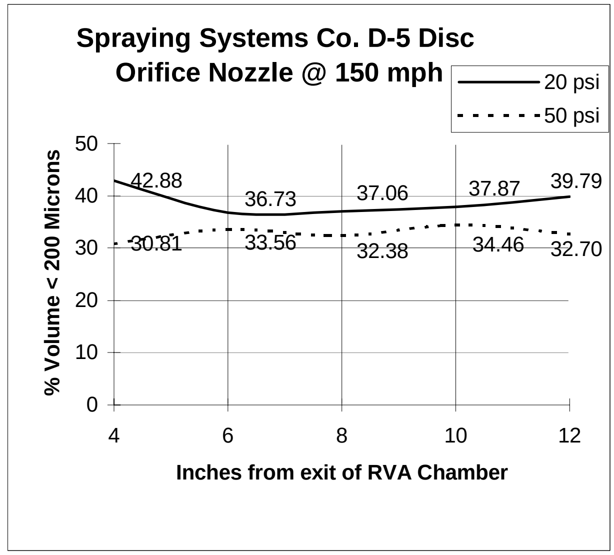


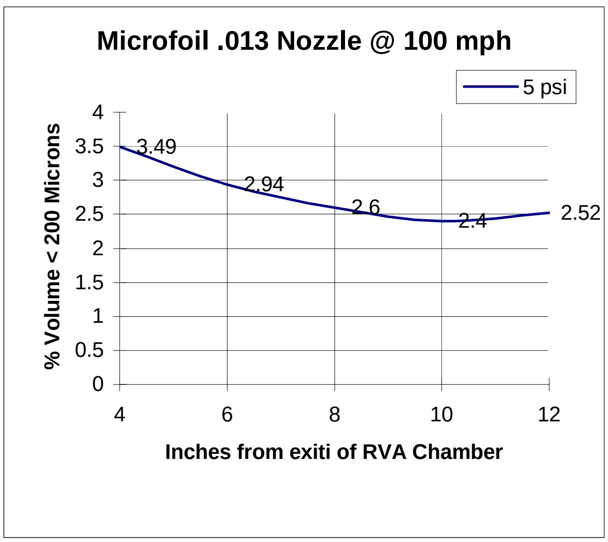


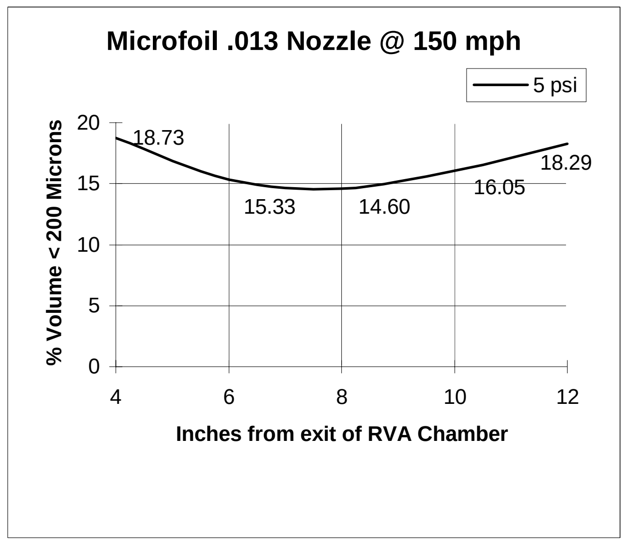


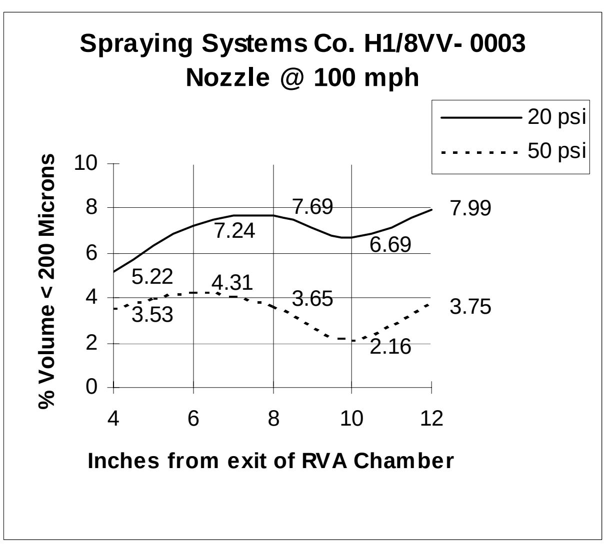


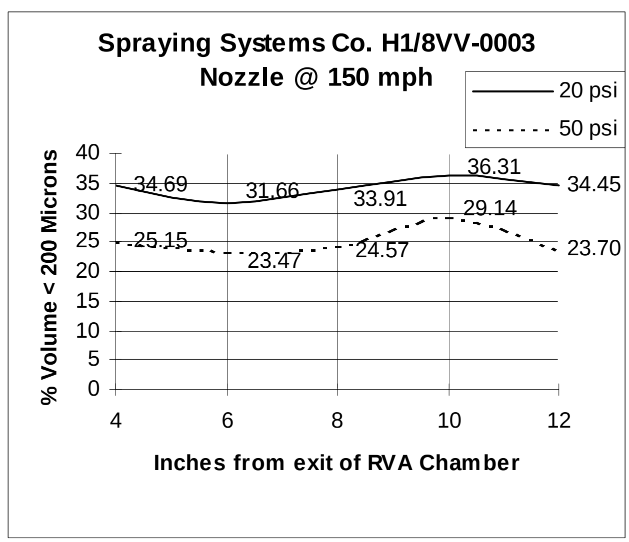

Spraying Systems Co. D-5 Disc Orifice Nozzle @ 100 mph
20 psi
50 psi
% Volume < 200 Microns
9
8
7
6
5
4
3
2
1
0
5.77
5.36
7.24
6.98
7.69
3.54
1.2
3.25
2.64
4
6
8
10
12
Inches from exit of RVA Chamber

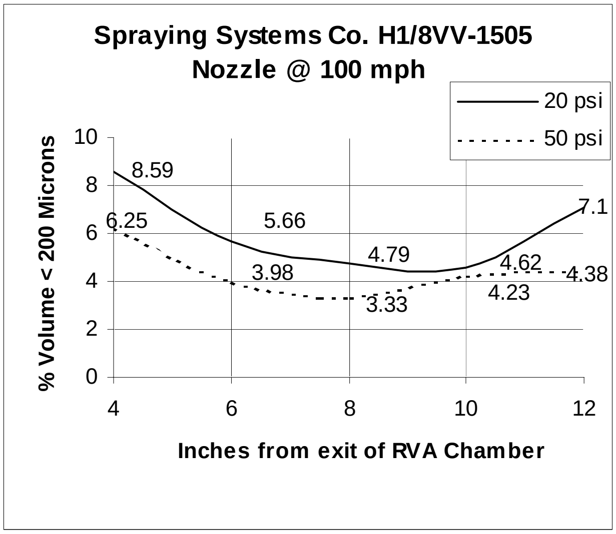

Spraying Systems Co. D-5 Disc Orifice Nozzle @ 150 mph
20 psi
50 psi
% Volume < 200 Microns
50
40
30
20
10
0
42.88
36.73
37.06
37.87
39.79
30.81
33.56
32.38
34.46
32.70
4
6
8
10
12
Inches from exit of RVA Chamber

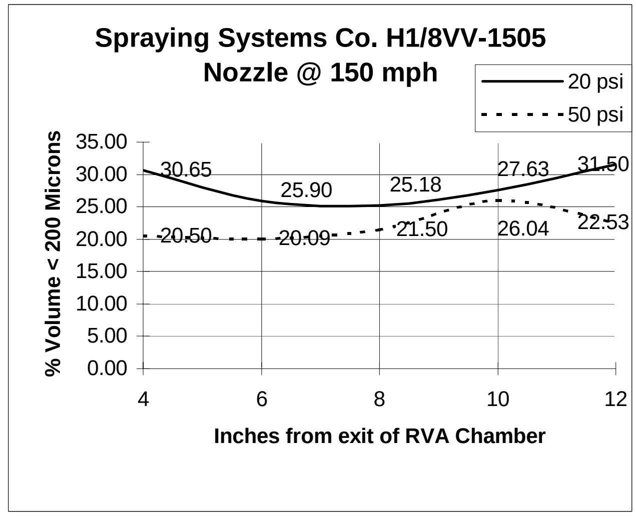

Microfoil .013 Nozzle @ 100 mph
5 psi
% Volume < 200 Microns
4
3.5
3
2.5
2
1.5
1
0.5
0
3.49
2.94
2.6
2.4
2.52
4
6
8
10
12
Inches from exiti of RVA Chamber

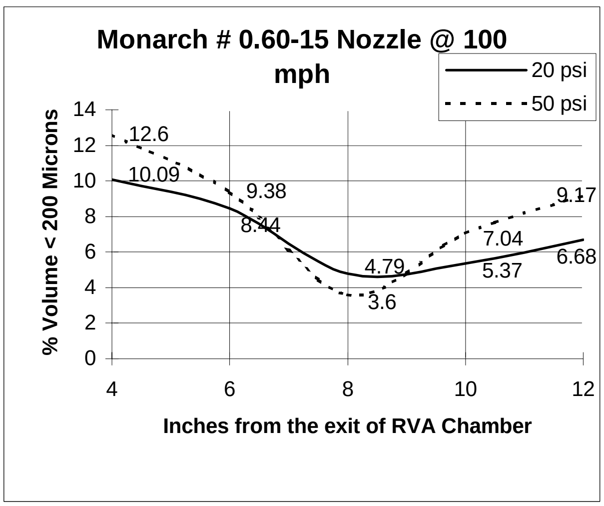

Microfoil .013 Nozzle @ 150 mph
5 psi
% Volume < 200 Microns
20
15
10
5
0
18.73
15.33
14.60
16.05
18.29
4
6
8
10
12
Inches from exit of RVA Chamber

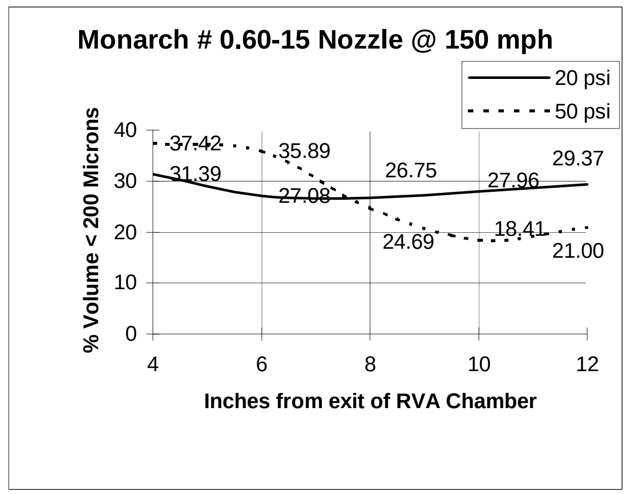

Spraying Systems Co. H1/8VV- 0003 Nozzle @ 100 mph
20 psi
50 psi
% Volume < 200 Microns
10
8
6
4
2
0
5.22
7.24
7.69
6.69
7.99
3.53
4.31
3.65
2.16
3.75
4
6
8
10
12
Inches from exit of RVA Chamber

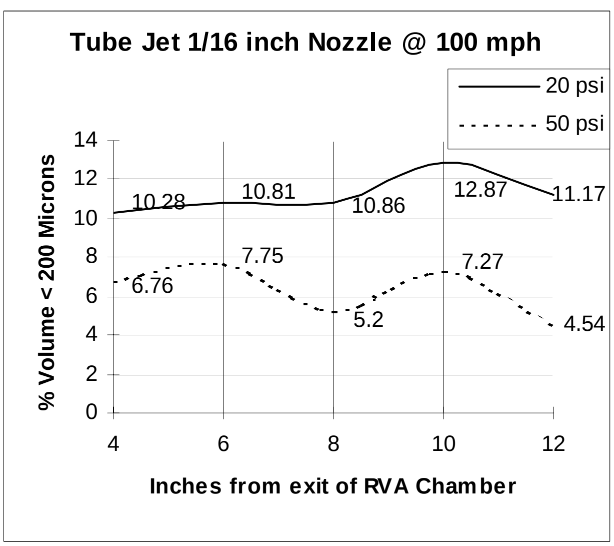

Spraying Systems Co. H1/8VV-0003 Nozzle @ 150 mph
20 psi
50 psi
% Volume < 200 Microns
40
35
30
25
20
15
10
5
0
34.69
31.66
33.91
36.31
34.45
25.15
23.47
24.57
29.14
23.70
4
6
8
10
12
Inches from exit of RVA Chamber

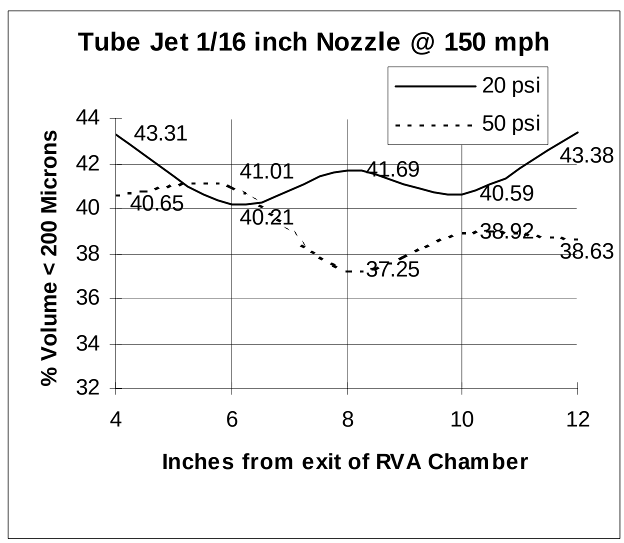

Spraying Systems Co. H1/8VV-1505 Nozzle @ 100 mph
20 psi
50 psi
% Volume < 200 Microns
Inches from exit of RVA Chamber
8.59
6.25
5.66
3.98
4.79
3.33
4.62
4.23
7.1
4.38


Spraying Systems Co. H1/8VV-1505 Nozzle @ 150 mph
20 psi
50 psi
% Volume < 200 Microns
Inches from exit of RVA Chamber
30.65
25.90
25.18
27.63
31.50
20.50
20.09
21.50
26.04
22.53


Monarch # 0.60-15 Nozzle @ 100 mph
20 psi
50 psi
% Volume < 200 Microns
Inches from the exit of RVA Chamber
12.6
10.09
9.38
8.44
4.79
3.6
7.04
5.37
9.17
6.68


Monarch # 0.60-15 Nozzle @ 150 mph
20 psi
50 psi
% Volume < 200 Microns
Inches from exit of RVA Chamber
37.42
31.39
35.89
27.08
26.75
24.69
27.96
18.41
29.37
21.00


Tube Jet 1/16 inch Nozzle @ 100 mph
20 psi
50 psi
% Volume < 200 Microns
Inches from exit of RVA Chamber
10.28
10.81
10.86
12.87
11.17
6.76
7.75
5.2
7.27
4.54


Tube Jet 1/16 inch Nozzle @ 150 mph
20 psi
50 psi
% Volume < 200 Microns
Inches from exit of RVA Chamber
43.31
40.65
41.01
40.21
41.69
37.25
40.59
38.92
43.38
38.63

Professor Akesson provided direction and assistance in the wind tunnel protocols. The University of California, Davis, wind tunnel uses a basic Particle Measuring Systems Company OAP-2D-GA-1, 2-dimensional analyzer to categorize the spray being tested into 64 channels having a drop diameter size range from 28 μ to 2062 μ. Bench tests established the spray pattern for each nozzle that was then compared with the spectrum obtained when the nozzle was operated in the chamber. Each nozzle was placed in Chamber 3 at five different locations, 4, 6, 8, 10, and 12 inches from the exit end of the chamber, using a sliding mount attached at the throat of the chamber, and evaluated in the wind tunnel at both 100 and 150 mph. The data collected have provided valuable information and an adequate baseline for further study. Tables 5 and 6 present the results of the testing of eight nozzles at the two airspeeds.

TABLE 5. Spray droplet comparisons of eight nozzles tested in the wind tunnel.

Data represent the average of three tests on each nozzle at 50 and 100 mph. Spray pressures vary, as described in the text. Percent reduction in fines is between the nozzle alone at 100 mph and the nozzle in the RVA chamber at 100 mph in the wind tunnel.

Nozzle	Air Velocity (mph)	Liquid pressure (psi)	Droplet Size Indicators			% of volume <200μ	R.S.	% ↓ in fines
			Dv 0.1	Dv 0.5	Dv 0.9			
H1/8VV-2505	50	20	554	963	1419	2.32	0.89	
H1/8VV-2505	100	20	172	577	908	13.16	1.30	73.8%
H1/8VV-2505+RVA	100	20	508	924	1311	3.45	0.87	
1/8MEG-1503	50	20	577	952	1346	2.40	0.81	
1/8MEG-1503	100	20	143	533	943	13.67	1.50	71.3%
1/8MEG-1503+RVA	100	20	484	920	1179	3.93	0.75	
D-5	50	50	877	1552	1993	2.09	0.78	
D-5	100	50	590	1549	1995	3.18	0.95	62.3%
D-5+RVA	100	50	958	1904	2026	1.20	0.56	
Microfoil .013	50	5	603	751	928	1.89	0.43	
Microfoil .013	100	5	463	732	907	4.14	0.61	42.0%
Microfoil .013+RVA	100	5	656	846	1021	2.40	0.43	
H1/8VV-0003	50	50	1242	1914	1997	2.14	0.40	
H1/8VV-0003	100	50	550	1504	1865	3.44	0.91	37.2%
H1/8VV-0003+RVA	100	50	928	1857	2019	2.16	0.59	
H1/8VV-1505	50	50	461	884	1289	4.21	0.94	
H1/8VV-1505	100	50	325	717	1094	4.92	1.07	32.3%
H1/8VV-1505+RVA	100	50	492	893	1293	3.33	0.90	
Monarch H-535#.60-15	50	50	340	780	1237	5.98	1.15	
Monarch H-535#.60-15	100	50	310	684	1128	5.02	1.19	28.3%
Monarch+RVA	100	50	410	828	1405	3.60	1.19	
TubeJet .06256	50	50	905	1771	1888	2.77	0.56	
TubeJet .0625	100	50	351	1004	1768	5.77	1.44	21.3%
TubeJet .0625	100	50	448	1329	1948	4.54	1.18	

TABLE 6. Spray droplet comparisons of eight nozzles tested in the wind tunnel.

Data represent the average of three tests on each nozzle at 75 and 150 mph. Spray pressures vary, as described in the text. Percent reduction in fines is between the nozzle alone at 150 mph and the nozzle in the RVA chamber at 150 mph in the wind tunnel.

Nozzle model	Air Velocity (mph)	Liquid pressure (psi)	Droplet Size Indicators			% of volume <200μ	R.S.	% ↓ in fines
			Dv 0.1	Dv 0.5	Dv 0.9			
H1/8VV-2505	75	50	301	652	975	6.52	1.03	
H1/8VV-2505	150	50	55	330	617	30.67	1.71	39.4%
H1/8VV-2505+RVA	150	50	79	479	717	18.58	1.34	
1/8MEG-1503	75	50	206	476	708	9.70	1.06	
1/8MEG-1503	150	50	56	310	567	31.71	1.65	58.6%
1/8MEG-1503+RVA	150	50	123	503	732	13.14	1.21	
D-5	75	50	386	1124	1657	7.93	1.13	
D-5	150	50	45	369	746	32.87	1.92	1.5 %
D-5+RVA	150	50	44	480	929	32.38	1.83	
Microfoil .013	75	5	476	664	847	3.58	.56	
Microfoil .013	150	5	51	270	477	34.20	1.47	55.2%
Microfoil .013+RVA	150	5	96	510	696	15.33	1.18	
H1/8VV-0003	75	50	1555	1787	1980	0.35	0.24	
H1/8VV-0003	150	50	71	467	739	19.50	1.43	-17.0%
H1/8VV-0003+RVA	150	50	55	504	847	23.47	1.57	
H1/8VV-1505	75	50	429	826	1173	6.89	.90	
H1/8VV-1505	150	50	55	372	619	25.49	1.52	21.2%
H1/8VV-1505+RVA	150	50	70	491	755	20.09	1.40	
Monarch H-535#.60-15	75	50	274	698	1051	7.89	1.11	
Monarch H-535#.60-15	150	50	58	342	592	26.92	1.56	31.6%
Monarch+RVA	150	50	73	516	781	18.41	1.37	
TubeJet .06256	75	50	205	1217	1646	10.43	1.20	
TubeJet .0625	150	50	48	307	710	35.77	2.14	-4.1%
TubeJet .0625	150	50	42	348	755	37.25	2.05	

In summary, the individual nozzles performed somewhat differently at 100 and 150 mph external air speed. At 100 mph, the 2505 flat fan nozzle demonstrated a 73.8% reduction in fines, the MEG-1503 flat even fan nozzle demonstrated a 71.3% reduction, and the D5 nozzle a 62.3% reduction. At 150 mph, the overall percent reduction in fines was less remarkable, ranging from 58.6 to 1.8%. At 150 mph, the 2505 and MEG-1503 nozzles still reduced fines, 39.4 and 58.6% respectively, but none of the nozzles performed as well at 150 mph as it had at 100 mph. The Microfoil 0.13 that had shown only 42.0% reduction at 100 mph, demonstrated a 55.2% reduction at 150 mph. Interestingly, D-5 nozzle that had shown 62.3% reduction in fines at 100 mph showed almost no reduction (1.5%) at 150 mph. This appears to be due to the fact that this is a solid stream nozzle and, because of the design of the chamber system, the stream does not actually break up into measurable droplets until the stream passed out of the chamber.

This allows the majority of the steam to be atomized out of the chamber in the higher air velocity. If the size of the orifice were smaller as in the micro jet nozzle, atomization takes place in the chamber. This characteristic may or may not turn out to be important in future chamber development.

Deviations between theoretical and actual values in the RVA chamber could in part be caused by air flow flutter or secondary atomization outside of the chamber. Improved chamber design and refinements will likely decrease this. Also, reducing wind velocities within the chamber to less than 50 or 75 mph could also have a significant impact on the reduction of fines.

By creating the droplets in the chamber where the wind speed was greatly reduced and then accelerating the droplets (by constricting the size of the chamber) to very close to the external airspeed, droplet shatter or fracture was greatly reduced and the proportion of particles in the Dv 0.5 range was increased. This was a key goal of this project and we believe we have been successful in these efforts. We hope this will have a secondary benefit, to be explored in a subsequent Phase I project. Previous efforts to reduce fines have tended to create an increase in larger droplets, in effect shifting the Gaussian curve toward larger droplets. We believe that, with proper design and proportions, combined with a nozzle producing a narrower droplet spectrum, the RVA chamber system will tend to compress the curve, minimizing both fines and larger droplets. With these refinements, the RVA chamber system may provide greatly more uniform droplet spectra.

Conclusions

The key technical objectives of the USDA SBIR Phase I proposal have been met or exceeded overall. An improved RVA chamber has been developed. A solution to the boundary layer problem within the chamber has been a significant accomplishment and has led us to additional investigative goals including an even more efficient chamber design. Considerable information has been developed on the behavior of spray nozzles in the wind tunnel. Additionally, the behavior of spray droplets in the improved RVA chamber has been determined and eight nozzles have been evaluated at 50, 100 and 150 mph in the chamber.

By reducing off-site spray drift and making it possible to treat more acres in a shorter period of time (and perhaps treating them more effectively), it may also be possible to reduce the cost of production of various food crops. This would help make the national food supply more affordable, or at least to help contain escalating production costs. By helping to contain escalating crop production costs, reducing off-site spray drift will subsequently help farmers maintain their position in the global agricultural market.

There are approximately 2500 agricultural aircraft operators flying some 3000 aircraft in the United States and <u>all</u> of those responding to the National Agricultural Aircraft Association's survey indicated that they apply liquid materials. The potential for post application utilization of the RVA chamber is significant. Wind is a component of concern for virtually all aerial applications, regardless of the speed at which the aircraft travels. Therefore, by implementing the RVA chamber as a strategy to reduce the percentage of fines produced by aerial applications, this research offers a potential benefit for all aerial applicators. The ability to deliver material in such a way as to minimize off-site drift and to do so under conditions such as light wind would be a significant benefit to both those who need the material applied and those performing the actual application of the material.

Acknowledgements

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References

Akesson N.B., Gibbs R.E., 1990. Pesticide drop size as a function of spray atomizers and liquid formulations, Pesticide Formulations and Applications Systems, 10th Vol., ASTM STP 1078, L. E. Bode, J.L. Hazen, D.G. Chasin (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 170-183.

Akesson N.B., Hitch R.K. and Jones A.W. An analysis of airborne transport of pesticides from large scale aerial applications. Environmental Protection Agency Conference on Spray Drift, Washington, D.C., September, 1996.

Akesson N.B., Steinke W.E., Yates W.E. 1994. Atomizer design for agricultural air shear applications. Pesticide formulation and Application Systems, 14th Vol. ASTM STP 1234, F.R. Hall, P.D. Berger, H.M. Collins (eds.), American Society for Testing and Materials, Philadelphia, PA.

Akesson N.B., Yates W.E. 1974. The use of aircraft in agriculture. FAO Agriculture Development Manual #94. FAO of the United Nations, Rome, Italy.

Akesson N.B., Yates W.E. 1989. Pesticide deposit and activity as a function of spray atomizers and liquid formulations. Proceedings, 11th International Congress on Agricultural Engineering (CIGR), Secretariat 22, Clyde Rd., Dublin, Ireland, Vol. 3, pp. 2081-2090.

Bouse L.F., 1992. Effect of nozzle type and operations on spray droplet size. NAAA-ASAE Paper No. AA91005, ASAE, St. Joseph, MI.

U.S. Forest Service, 1990. Compendium of drop size spectra compiled from wind tunnel tests, compiled by P.J. Skyler, J.W. Barry. United States Department of Agriculture, Forest Pest Management, FPM 90-9. Davis, CA

Kirk I.W., 2000. Spray quality for helicopter spray nozzles. NAAA/ASAE Joint Technical Session, Reno, NV, No. AA00-006, ASAE, St. Joseph, MI.

Kirk I.W., 2001. Droplet spectra classification for fixed-wing aircraft spray nozzles. ASAE International Meeting, Sacramento, CA, No. 01-1082, ASAE, St. Joseph, MI

Wilce S.E., Akesson N.B., Yates W.E. 1974. Drop size control and aircraft spray equipment. Agricultural Aviation Institute, Cranfield Research Center, Bedford, England, 16(1):7-11.

Womac A.R., Williford J.R., Weber B.J., Pearce K.T., Reichard D.L. 1992. Influence of pulse signal and liquid characteristics on performance of uniform - droplet generation. Transactions of the ASAE, St. Joseph, MI, 35(1):71-79.

Yates W.E., Cowden R.E., Akesson N.B., 1983a. Nozzle design influence on uniformity of droplet size spectrum from agricultural aircraft. Transactions of the ASAE. St. Joseph, MI, 26(6):1633-1637.

Yates W.E., Cowden R.E., Akesson N.B. 1983b. Nozzle orientation, air speed and spray formulation, effects on drop size spectrums. Transactions of the ASAE, St. Joseph, MI, 26(6):1638-1643.